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Internal combustion engines: Progress and prospects

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ABSTRACT

Indeed, the engine industries have seen a tremendous growth in the research and development of new-age technologies over the past ten years or so. Even though a huge database is now available on present-day engine technologies, a skillful presentation of those data is a demanding task. At this count, an endeavor has been made here to brief the pros and cons of present-day engine technologies in an elusive manner. In a nut–shell, this article provides an extensive review of the primary principles that preside over the internal combustion engines design and operation, as well as a simplifying framework of new-age engine technologies has been organized and summarized in an elegant way to contribute to this pragmatic field.

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1. Introduction

Perhaps the most graceful invention by humankind that ever had a greater impact on society, the economy, and the environment is the reciprocating internal combustion engines, in general called as IC engines [1,2]. Although several researchers made noteworthy contributions in the development of IC engines, the historical breakthrough by Nicolaus Otto (1876) and his counterpart Rudolf Diesel (1892) in the development of Spark Ignition (SI) engine and Compression Ignition (CI) engine is globally praised [3,4]. For decades, their magnificent inventions proved to play a vital role in the automobile system, used almost exclusively today.

Unfortunately, at present there is a pressing need to develop advanced combustion engines that maximize the engine efficiency and totally mitigate the exhaust emissions [5,6]. In this regard, the hybrid electric vehicles would be the major part of future transportation systems, because of their eco-friendliness and flexibility in operation [7]. Conversely, there are issues like power storage options allied with hybrid electric vehicles yet to be resolved [8]. Thus, undoubtedly hybrid vehicles would be the new age eco-friendly vehicles, which would find a potential global market in near future.

However, focusing on the present day scenario, several studies have been conducted on improving the performance of conventional IC engines by using alternate fuels, without much modification in the engine system [9–12]. Since more than enough of the research studies had been carried out in analyzing the performance and emissions of conventional IC engines by alternate fuels, an attempt has been made in this article to devise the principle design and operating variables, such as compression ratio, ignition period, injection parameters, etc., that influence the engine operation under diverse circumstances. In conjunction, an exertion has been made to discuss briefly the pros and cons associated with non-conventional IC engine's operation.

2. Variables influencing engine performance

While designing any potential heat engine, a formidable challenge lies in designing it to produce a twin advantage of maximum mechanical power and minimum engine-out exhaust, by supplying less energy input to the engine. Although 100% occurrence of the above incident is cumbersome, however, to some extent, the engine's performance could be influenced by varying the design and operating variables. Amongst several variables, the emphasis here is on the combustion chamber geometry, compression ratio, exhaust gas recirculation (EGR), ignition delay, injection parameters, and intake system heating.

2.1. Combustion chamber geometry

2.1.1. Open combustion chamber

In general, a typical IC engine's performance, emission, and combustion characteristics strongly rely on the combustion chamber configuration. To assist the above fact, several noteworthy experimental investigations on the effects of varying combustion chamber geometry were demonstrated by numerous researchers. In that count, Jaichandar et al. [13] studied the effects of varying the open combustion chamber geometry in a single cylinder diesel engine fueled with Pongamia methyl ester. The experimental outcomes revealed improved characteristics for the toroidal combustion chamber when compared to the shallow depth combustion chamber and hemispherical combustion chamber. This trend was principally due to the improved air motion by employing toroidal combustion chamber, which might have enhanced the mixture preparation and combustion mechanism. In the sequence with the above work, a significant contribution was made by Mamilla et al. [14] in evaluating the effects on engine performance by varying the open combustion chamber geometry. The study was carried out in a single cylinder, direct-injection diesel engine fueled with Jatropha bio-diesel. The experimental outcomes proved superior performance characteristics for the toroidal combustion chamber when compared to the other open type combustion chambers.

Besides the experimental investigations on the effects of combustion chamber configurations, various optimization techniques to evaluate the effects of combustion chamber geometry on engine performance were carried out by several researchers. One such contribution was made by Park [15]. Park evaluated the effects of optimization of combustion chamber geometry and engine operating conditions for CI engines fueled with di-methyl ether (DME). In the study, the DME was chosen as an alternative fuel to diesel since DME roughly contains about 35 wt% of oxygen, which would improve the combustion characteristics. In addition, the study stressed the need of optimization of combustion chamber to achieve considerable improvement in the engine operating characteristics.

2.1.2. Divided combustion chamber

In the past twenty five years or so, abundant research works had been carried out in a direct injection combustion chamber (open combustion chamber) than indirect-injection combustion chamber (divided combustion chamber). This is due to the fact that the use of the divided combustion chamber is often accompanied by high fuel penalties. However, with divided combustion chamber design, vigorous charge motions and faster combustion rates can be achieved [16]. In this regard, Rakopoulos et al. [17] dealt with the determination of combustion mechanisms in the divided combustion chamber. The analysis results provided a basis for construction of the divided combustion chamber, and exhibited the most appealing results with heat release rate mechanism.

2.2. Compression ratio

Like the combustion chamber configuration, the compression ratio (CR) is also an equally important design parameter that has a momentous effect on performance and emission characteristics, because CR is a chief concern for flexible fuel technology development [18]. To substantiate the above actuality, several research works had been carried out by the analysts throughout the world. Below are some of the remarkable contributions made by the researches on the effects of varying CR on the engine performance.

Raheman and Ghadge [19] studied the impact of varying CR of a Ricardo diesel engine fueled with Mahua bio-diesel. It was apparent from the study that the performance characteristics of diesel engine fueled with B20 (20% bio-diesel and 80% diesel) Mauha bio-diesel by varying compression ratio from 18:1 to 20:1 disclosed about 29.5% increase in brake thermal efficiency (BTE). Similar to prior work, Sayin and Gumus [20] investigated the influence of CR on a single cylinder, direct-injection diesel engine fueled with bio-diesel blended diesel fuel. The experimental results showed substantial improvements in BTE, fuel economy, CO, HC, and smoke opacity along with sharp increase in NO_x emission when the CR was raised from the standard settings.

In recent days, gaseous fuels are attractive owing to their ability to form near homogenous mixture and due to their wider flammability limits. An experimental work by Porpatham et al. [21] on the effects of CR on the performance mechanism of a modified diesel engine operated with bio-gas revealed an increase in BTE, HC and NO emissions to increase in CR. This significant increase was noted to be the highest at the CR of 15:1. The chief reason for

this trend was noted to be the increase in combustion rate and the reduction in delay period when CR increases.

A different study by Çelik et al. [22] on the use of pure methanol as sole fuel in a single cylinder gasoline engine at high CR of 10:1 exhibited increase in engine power and BTE of about 14% and 36%, respectively. On the other hand, obvious reductions in CO, CO_2 and NO*x* emissions (except HC emission) were noticed at high CR of 10:1. The primary reason for this exponential increase in HC emission with CR was found to be the increase in surface/volume ratio with the increase in CR.

Yet another assessment of the consequence of varying CR on the engine performance was examined by Yücesu et al. [23]. A single cylinder, four-stroke gasoline engine fueled with ethanol–gasoline blends was chosen to inspect the engine characteristics. In the study, both the performance and emission characteristics were found to be good in accordance with higher CR.

A recent study by Pan et al. [24] on the dual effects of EGR and CR in a port fuel injected gasoline engine at wide open throttle operation portrayed a major reduction in cyclic variations by increasing CR for a given EGR ratio. This trend was predominantly due to the influence of laminar flame speed and turbulent intensity, which increased with increase in CR for both experimental as well as computational analysis.

2.3. Exhaust gas recirculation (EGR)

Nowadays, in order to meet stringent vehicular emission norms, automotive engineers world-wide scuffle on designing new technologies to considerably reduce the exhaust emissions. In this regard, EGR technique would be the most effective pretreatment technique to combat NO*x* emission [25,26]. The estimation made by a few scholars on the effects of EGR on the engine performance and emission characteristics has been elaborated in the upcoming paragraphs.

Agarwal et al. [27] evaluated the adverse effects of EGR on diesel engine operational characteristics. The evaluation confirmed substantial reduction in NO*x* emission. But, the HC, CO and smoke emissions exponentially increased with increasing EGR rates. However, the most pleasing engine performance in terms of the BTE, fuel economy, and emissions was found to be apparent up to 15% EGR rates. Yet another evaluation by Agarwal et al. [28] concluded that the simultaneous reduction in NO*x* and smoke emission was evident when both bio-diesel and EGR were employed in diesel engines.

Another study by Saleh et al. [29] on the impact of EGR on the diesel engine characteristics operated with Jojoba methyl ester disclosed better emission trade-off characteristics when the optimal EGR level of 12% was maintained. Also, the study reported that 50–55% of NO*x* reduced at higher EGR rates of 25–40%, above which the combustion characteristics deteriorated.

2.4. Ignition delay

On behalf of engine performance analysis, the determination of optimal ignition timing is a key issue of study. The contributions made by some researchers on the effect of varying ignition timings on engine performance and emissions have been presented in the subsequent paragraphs.

An in-depth study on the effects of varying ignition timings on a gasoline engine operated with methanol was analyzed by Li et al. [30]. They found improvements in BTE, in-cylinder pressure, cyclic variation, and heat release rate at an optimal ignition timing. And, this optimal value was noted to be 18° CA BTDC.

In addition, a systematic measurement of ignition delay for jet fuels and diesel fuel in a heavy-duty, single cylinder diesel engine was done by Rothamer and Murphy [31]. Their measurements showed good harmony of the measured values with Arrhenius expressions.

In the same way, predictive correlations for the determination of the ignition delay period for bio-diesel fueled diesel engine were developed by Verhelst et al. [32]. The new correlations were developed taking into consideration of the major parameters like equivalence ratio, the cylinder pressure and temperature. And, hopeful results were noted with the values predicted by new correlations. Likewise, Kasaby and Nemit [33] works on the measurement of the delay period for different Jatropha bio-diesel blends too exhibited reduction in delay period with increase in pressure, temperature and equivalence ratio.

2.5. Preheating

For a long period, heating induction system to assist fuel vaporization under the cold engine operation was employed [34]. To legalize the above statement, numerous literature studies had been carried out. Among those, the notable works are collectively organized and presented here.

2.5.1. Air preheating

Yilmaz [35,36] investigated the effects of intake air preheating on the performance and emission trends of a diesel engine fueled with bio-diesel–alcohol blends. In the study, the intake air was preheated to the upper limit of 85 °C. Based on the study, it was clearly suggested that complete combustion of bio-diesel in a diesel engine could be guaranteed by operating the engine with bio-diesel–alcohol (either methanol or ethanol) blends under warm environment.

2.5.2. Fuel preheating

An investigation by Raheman et al. [37] on the effects of preheating Jatropha oil by means of residual gas exhibited greater influence on the performance and emission characteristics. For the purpose of preheating, a helical coil heat exchanger was fitted to raise the temperature of Jatropha oil, and the inlet temperature of the oil was maintained within a range of ± 70 °C throughout the mode of engine operation. Overall, the experimental results indicated lower BTE and higher fuel consumption for preheated Jatropha oil when compared to neat diesel operation. On the other hand, the reduced emission trends were also witnessed due to preheating.

Another investigation on the effect of fuel preheating was critically evaluated by Hazar and Aydin [38]. In the study, the performance and emission behavior of a CI engine fueled with preheated Rapeseed oil–diesel blends were explored. Hazar and Aydin elucidated in their work that the use of preheated oil–diesel blends would offer smooth fuel flow with total evasion of fuel filter clogging. This trend was primarily accomplished in their study by preheating the oil to 100 °C. Also, the study clarified that the effect of preheating fuels tends to lower the power output as the result of higher leakages in the pump and injector. Furthermore, analogous remarks on the effects of fuel preheating were noted by Bari et al. [39].

2.6. Injection parameters

In line with other variables, the effect of injection parameters on engine performance is of prime interest of study. In the following sections, the effects of injection pressure, injection timing, and water injection on engine performance and emissions have been expatiated.

2.6.1. Injection pressure

Gumus et al. [40] analyzed the crucial effects of increasing the fuel injection pressure in a direct injection diesel engine operated with bio-diesel–diesel blends. For this study, four different injection pressures (180, 200, 220, and 240 bar) were considered to evaluate the engine operation over the wide range of injection pressures. The experimental outcomes revealed improvements in fuel economy, HC, CO and smoke opacity, whereas a reverse trend was noted with CO_2 and NO*x* emissions. In addition to, evaluations made by Kannan and Anand [41] on the effects of varying injection pressure in a diesel engine operated with distrol fuel (a blend of 30% waste cooking oil methyl ester, 60% diesel and 10% ethanol) exhibited maximum BTE of around 31% at an optimum injection pressure of 240 bar. As well, due to the effect of increasing the injection pressure, engine-out exhausts reduced considerably.

Similarly, studies by Çelikten [42] and Puhan et al. [43] on the effects of injection pressure on engine operation disclosed enhancement in performance and emission characteristics.

2.6.2. Injection timing

To optimize the engine characteristics, various injection strategies such as multiple injections, injection angles, and advanced injection timings were adopted by many researchers [44,45]. Hereby, the highlight is made on the effects of the advancement of injection timings on engine operational behavior.

Nwafor et al. [46] presented the effects of advancing injection timings of a single-cylinder, energy cell (indirect injection) diesel engine fueled with crude rapeseed oil. They made a comparable assessment on the effects of increasing the injection timings from the standard setting of 30 °C BTDC to 33.5 °C BTDC and 35.5 °C BTDC. The test results showed smooth engine operation at 33.5 °C BTDC and rough engine operation during 35.5 °C BTDC. Therefore, it was concluded from the study that the advancement of injection timings fundamentally depends on the combustion duration of particular fuels. In continuity of the above work, Nwafor [47] evaluated the effects of advancing injection timings on engine emissions using natural gas. The test results showed significant reductions in Greenhouse gas emissions (CO and CO_2) with advanced timings. Apart from the experimental evaluations, simulation analysis too proved reduction in exhaust emissions at advanced injection strategies [48].

2.6.3. Water emulsion/injection

To overcome CI engine's shortcomings of poor fuel atomization and high NO*x* emission, the water injection process in the combustion chamber has been proposed [49,50]. The effects of water injection on engine performance dealt in two recent research works have been discussed in the following paragraphs.

A detailed experimental study by Fahd et al. [51] on the effects of 10% water emulsion in a direct injection diesel engine projected comparable values of BTE when compared to without emulsion. Moreover, substantial reductions in NO and CO emissions at maximum load operation were witnessed. Besides water/diesel emulsion technique to suppress NO*x* emission in CI engine, water injection on the intake manifold or direct injection of water inside the combustion chamber could be employed to lessen NO*x* emission [52]. In this regard, reports by Tesfa et al. [52] revealed that water injection in the intake manifold would considerably reduce the NO*x* emission by affecting the premixed combustion temperature, which forms a basis for NO*x* formation. Furthermore, the results proved that the power output and fuel economy were unaltered during water injection.

Based on the above observations, the inferences made by researchers on the effects of fundamental design and operating variables on engine characteristics are organized in a simplified manner and presented in Table 1.

On the whole, the following variables play a vital role in modern engine development.

In case of SI engines, principle design parameters like compression ratio, combustion chamber geometry, spark timing, design of intake ports for creating desired air motion (especially high swirl to increase burn rate), etc., have to be optimized to significantly reduce emissions. Conjointly, significant improvements in fuel efficiency can be attained by improving gas exchange process, reducing pumping and heat loss at part loads, adoption of multi-valves cylinders, variable valve actuation for varying valve timings and lift, direct injection concept, engine downsizing, variable swept volume, supercharging, etc.

On the other hand, in case of CI engines, significant improvements in combustion and substantial reductions in emissions (particularly NO*x* and PM) can be attained by optimization of combustion chamber design and in-cylinder air flow, use of high fuel injection pressure along with small nozzle hole diameter to enhance fuel atomization, optimizing ignition quality, volatility and aromatic content of fuel, precise control of injection rate and injection rate shaping, multiple injections, EGR, variable boost pressure, etc.

3. Non-conventional IC engines operation

Over the last few decades, intensified efforts by several researchers to improve the conventional IC engine performance primarily lead to the development of non-conventional IC engines. Among a number of non-conventional IC engines, the emphasis here is on the dual-fuel engine, free-piston engine, gasoline direct injection engine, homogeneous charge compression ignition engine, lean-burn engine, and variable compression ratio engine.

3.1. Dual-fuel engine

Reiter and Kong [53] investigated the combustion and emission characteristics of a CI engine using ammonia–diesel dual-fuel system. The primary observations exhibited the most encouraging results in terms of fuel economy by using 40–60% concentration of diesel in ammonia–diesel dual-fuel. Conversely, below 40% unfavorable results were noticed in terms of fuel economy. And, when the concentration exceeded above 60%, the combustion efficiency ruined. On the whole, the study suggested the need to impose varied injection strategies to optimize the combustion efficiency of ammonia–diesel dual-fuel engine.

Furthermore, Selim [54] analyzed the mechanism of combustion noise and its cyclic variations in a single cylinder diesel engine using diesel–liquefied petroleum gas (LPG) and diesel–methane dual-fuels. The test results indicated higher combustion noise and cyclic variations under diesel–LPG dual-fuel combustion than diesel–methane dual-fuel combustion. Also, by the influence of various strategies like increasing CR, advancing the injection timing, and by increasing the mass of pilot fuel exhibited an analogous trend. However, the combustion noise and its cyclic variations were drastically reduced with decreasing engine speeds. Yet another study by Saleh [55] uncovered the effects of varying LPG compositions on dual-fuel engine performance and emission characteristics. The study indicated that dual-fuel comprising 40% mass fraction of diesel fuel with roughly 30% butane content in LPG would improve the engine operating characteristics.

Similarly, Papagiannakis et al. [56] witnessed extensive reductions in NO and soot emissions by using natural gas/diesel dual-fuel technique. Yet, BTE, CO, and HC trends were greatly affected during natural gas/diesel dual-fuel combustion. Also, observations

Table 1
Effects of engine variables on engine performance.

Refs.	Test fuel	Design consideration	Variables treated	Inferences made
[13]	Pongamia methyl ester	Toroidal combustion chamber	–	Higher BTE (30.3%) with substantial reductions in HC (6%), CO (12%) and smoke density (20%) when compared to standard engine with diesel operation.
[14]	Jatropha Bio-diesel	Spherical, toroidal and re-entrant combustion chambers		Higher BTE (33.92%) with reductions in smoke density, carbon monoxide and hydrocarbons were witnessed for toroidal combustion chamber.
[15]	Di-methyl ether	Combustion chamber geometry (optimized)		Improvement in merit value (136%) was noted during the optimization process from the baseline to the optimized design.
[17]	Diesel	Divided combustion chamber	–	Enhancement in heat release rate accompanied by high fuel penalty.
[18]	Ethanol/gasoline blend and hydrous ethanol	–	CR	Improved engine performance for both fuels throughout all the speed range at higher compression ratios.
[19]	Mahua bio-diesel	–	CR	Almost same engine performance as that with diesel at any of the compression ratio.
[20]	Bio-diesel blended diesel	–	CR	With the increase in CR, BSFC and BTE considerably improved. Also, smoke opacity, CO and HC emissions reduced with the increase in CR.
[21]	Bio-gas	–	CR	10% increase in power output along with reduction in delay period at CR of 15:1.
[22]	Methanol	–	CR	Improvements in BTE (36%) and engine power (14%) together with considerable reductions in CO (37%), CO_2 (30%) and NO*x* (22%) emissions by increasing CR from 6:1 to 10:1.
[23]	Ethanol–gasoline blends	–	CR	Both the performance and emission characteristics were found to be good at higher compression ratio.
[27]	Diesel	–	EGR	The most pleasing engine performance in terms of BTE, fuel economy and emissions were found to be apparent up to 15% EGR rates.
[29]	Jojoba methyl ester	–	EGR	50–55% reduction on NO*x* at higher EGR rates of 25–40%.
[35]	Bio-diesel–methanol blends	–	Air preheating	Prospective reductions in HC and CO emissions with sharp increase in NO*x* emission at an elevated preheat temperature of 85 °C.
[36]	Bio-diesel–alcohol blends	–	Air preheating	Potential reductions in CO and HC emissions due to the effect of intake air preheating.
[37]	Jatropha oil	–	Fuel preheating	Substantial reductions in CO_2 (5.28%), HC (2.67%) and NO*x* (37.2%) emissions with steep raise in CO (85.63%) emission.
[38]	Rapeseed oil–diesel blends	–	Fuel preheating	Some positive effects on the engine performance and emissions when the rapeseed oil was heated to 100 °C.
[39]	Crude palm oil	–	Fuel preheating	Heating of crude palm oil (up to 100 °C) showed no significant advantages in terms of performance, but was necessary for the fuel to flow smoothly in the fuel system.
[40]	Bio-diesel–diesel blends	–	Injection pressure	Improvements in HC, CO and smoke opacity with increase in CO_2, O_2 and NO*x* emissions.
[41]	Diestrol fuel	–	Injection pressure and timings	Significant improvement in performance, combustion and reduction in emission characteristics at an optimum injection pressure (240 bar) and injection timing (25.5° bTDC).
[46]	Crude rapeseed oil	–	Injection timing	Drastic reduction in mechanical efficiency with significant improvements in CO and CO_2 emissions at optimal injection advancements.
[51]	Diesel	–	Water emulsion	Improvements in fuel economy with diminution of exhaust gas temperature and NO emission for 10% water emulsion.
[52]	Rapeseed oil bio-diesel	–	Water emulsion	Without any loss of power and any negative effect on fuel consumption, the water injection into the intake manifold can be employed to reduce NO*x* emission (up to 50%).

made by Lakshmanan and Nagarajan [57,58] obviously depicted that the implementation of port-fuel injection technique under dual-fuel mode in a direct injection diesel engine, using diesel as the primary fuel and acetylene gas as secondary fuel could greatly reduce the engine-out exhausts, seldom affecting the engine's brake thermal efficiency.

The effects of pilot injection timings on engine behavior under diesel–compressed natural gas (CNG) dual-fuel mode and bio-diesel–CNG dual-fuel mode was assessed by Liu et al. [59] and Ryu [60]. The test results indicated a 30% reduction in NO*x* emission with an increase in PM emission during diesel–CNG dual-fuel combustion by raising the pilot fuel quantity. On the other hand, marginal reduction in smoke emission and steep rise in NO*x* emission with the advancement of pilot injection timing was evident from bio-diesel–CNG dual-fuel engine.

Likewise, investigations of CI engine behavior by bio-diesel–biogas dual-fuel combustion showed significant reductions in soot and NO*x* emissions together with higher concentration of HC and CO emissions. Also, superior thermal efficiency by abetting super-charged mixing system under bio-diesel–biogas dual-fuel technique was apparent [61,62]. In addition to, significant advantages were noted with Greenhouse gas emissions by converting the conventional diesel engine run as a diesel–ethanol dual-fuel engine and diesel–hydrogen dual-fuel engine [63,64].

3.2. Free-piston engine

The term free-piston has been proposed to distinguish a linear engine from the rotary shaft engine. In fact, free-piston engines are 'crank less' engines, wherein the reciprocating piston is directly coupled to a linear load device such as hydraulic pump, so the piston motion is not restricted by the position of rotating crank-shaft as in conventional engines [65]. The recent reports submitted by some researchers on free-piston engine developments have been presented here.

Xiao et al. [66] studied the motion characteristics of a free-piston linear alternator. The study projected that free-piston linear alternator would be an effective energy conversion device due to its continuous power generation with low friction and noise. Additionally, to improve the dynamic performance of the piston motion and engine compression ratio, the piston motion control scheme has to be developed for free-piston IC engines [67]. Furthermore, recent research works on free-piston engines are focused on the development of hydraulic free-piston engines, because of their potential advantages of simplicity, low frictional loss, less maintenance cost, and higher operational flexibility [68]. In this view, an experimental study conducted by Zhao et al. [68] proved that hydraulic free-piston engines are competent energy conversion devices with which the maximum indicated thermal

Table 2
Operational behavior of non-conventional IC engines.

Engine type	Operation
Dual-fuel engine	Dual-fuel engine operates on two fuels. Of which, one is gaseous fuel called primary fuel is either introduced along with intake air or injected directly into the engine cylinder and compressed but does not auto-ignite due to its very high self-ignition temperature. And, the ignition of homogeneous air–gas mixture is accomplished by timed injection of small quantity of diesel called pilot fuel near the end of the compression stroke [57].
Free-piston engine	Free-piston engines are 'crank less' engines, wherein the piston is directly coupled to a linear load device such as hydraulic pump or electric power, so the piston motion is not restricted by the position of rotating crankshaft as in conventional IC engines [65].
GDI engine	In a GDI engine, the fuel injection is made directly into the cylinder avoiding the fuel film related problems in the port. The other remarkable advantages with GDI are the fuel cut-off in deceleration and the cooling of the inducted charge. Also, the evaporation of the fuel droplets cools the air and this allows higher compression ratios and lowers the octane requirement of fuels. In addition, the volumetric efficiency can be improved if the injection occurs during the induction event [70].
HCCI engine	HCCI engine is a hybrid of conventional SI and CI engines. The HCCI ignition is controlled by the charge mixture composition and its temperature history. So, HCCI is a capable alternative combustion technology to produce near zero NO*x* and soot emissions with high fuel efficiency [82].
Lean-burn engine	In lean-burn engine, relative air–fuel ratio used is higher than the stoichiometric requirements. Therefore, lean operation is an attractive operational condition; it is known as one of the techniques to enhance the thermal efficiency, fuel economy, and to decrease exhaust emissions [88].
VCR engine	In VCR engine, a relatively high compression ratio is employed for excellent stability at low load operation, and low compression ratio is used at full load operation to achieve high specific outputs [98].

efficiency (41%) and higher indicated mean effective pressure (5.2 bar) could be obtained by means of a constant volume combustion process. In addition, there is a necessity to optimize cycle-to-cycle variations in piston dynamics and cycle stability of hydraulic free-piston engines in future studies [69].

3.3. *Gasoline direct injection (GDI) engine*

From the time when cleaner emissions and fuel economy targets became apparent, the automotive manufacturers' worldwide focused on the development of a dominant IC engine, which could offer diesel like efficiency and gasoline specific power. In this view, GDI engines are more attractive, and could serve better in the place of conventional SI engines.

Apart from visible advantages, there are several constraints coupled with the GDI engines operation, however, to be resolved. In GDI engines, the fuel injection is made directly into the combustion chamber, so within this short span of time, the better mixture formation and evaporation considerably reduces [70]. In this view, the primary interest of study lies in inspecting the fuel sprays characteristics and atomization performance of GDI engines. One such investigation was carried out by Park et al. [71]. Their study was concerned with evaluating the spray behavior and atomization performance of three different fuels, such as neat gasoline, bio-ethanol and bio-ethanol/gasoline blends. Their evaluations confirmed that among three test fuels, bio-ethanol had a larger droplet size region than the other two. Thus, the use of bio-ethanol/gasoline blends could afford better combustion characteristics in GDI engines. To visualize this trend, the combustion performance of a GDI engine using gasoline/bio-ethanol blends was inspected by Turner et al. [72]. Their experimental test was carried out on a direct injection spark ignition engine at part load and speed conditions. The experimental outcomes revealed improvements in engine efficiency and combustion stability with reduced combustion initiation duration due to the fact of higher flame speeds and advanced combustion.

Furthermore, the spray pattern and mixture preparation play a foremost role in PM emission from direct injection SI engines [73,74]. The preliminary investigation by Myung et al. [75] on the control of PM emission from direct injection SI engines disclosed superior control of PM emission by the optimization of the engine operating variables and fuel injection strategies. Therefore, future research and development works have to be concentrated on GDI engines to optimize the engine performance, emission and combustion characteristics by controlling engine variables.

3.4. *Homogeneous charge compression ignition (HCCI) engine*

HCCI engines combine the best features of conventional SI and CI engines. In HCCI engines, the pre-mixed air–fuel mixture is inducted as in conventional SI engine and the auto-ignition process takes place as in the conventional CI engine. Thus, HCCI is a promising alternative combustion technology to produce near zero NO*x* and soot emissions with high fuel efficiency [76–79].

Cinar et al. [80] evaluated the effects of pre-mixed ratio of di-ethyl ether (DEE) on combustion and exhaust mechanism of a single-cylinder direct injection diesel engine. In their study, the pre-mixed fuel–air ratio was varied from 0% to the maximum of 30%, due the fact that the pre-mixed ratio above 30% resulted in audible knock. The experimental outcomes revealed distinct cyclic variations with increase in pre-mixed fuel–air ratio. But, with increase in pre-mixed fuel ratio of DEE, the NO*x* and soot emissions drastically decreased.

Overall, in most of the literature works, drastic reduction in NO*x* and soot emissions from the HCCI engine using pre-mixed fuels were confirmed [81,82]. At the same time, experimental study by Wang et al. [83] disclosed negative trends with NO*x* levels with an increase in the DEE ratio in a DEE-diesel dual-fuel pre-mixed charge compression ignition engine. As a result, the characteristics of HCCI engines strongly depend on the mode of engine operation.

In most cases, HC and CO emissions greatly suffered during HCCI operation due to the greater influence of cylinder crevices and local air–fuel equivalence ratio. However, the increasing HC and CO emissions during HCCI mode operation could be easily reduced by using direct oxidation catalysts and by the influence of second fuel injection timings as suggested by Fang et al. [84] and Turkcan et al. [85].

Also, to overcome the lack of combustion stability in HCCI engines several control strategies could be employed. A recent report portrayed that the assistance of spark in the HCCI combustion process could effectively control cycle-to-cycle variations and combustion phasing [86].

3.5. *Lean-burn engine*

The lean-burn engine is one of the advanced technologies to obtain superior fuel efficiency and thermal efficiency. However, lean-burn operation requires effective control of NO*x* emission and cycle-to-cycle variations [87,88]. In this regard, various methods to control cyclic variations and NO*x* emission during the lean-burn combustion are discussed below.

Table 3
Pros and cons of non-conventional IC engines.

Engine type	Pros	Cons
Dual-fuel engine [56,61,62,102]	Fuel diversity, clean-fuel burning, diesel-like efficiency and brake mean effective pressure along with much lower emissions (especially of oxides of nitrogen (NO*x*) and particulate matter).	Dual-fuel conversions suffer from major increases in carbon monoxide (CO) and hydrocarbon (HC) emissions and loss of fuel efficiency at light loads.
HCCI engine [76,78,103]	Improvements in fuel economy and thermal efficiency with significantly lower NO*x* and soot emissions.	Difficult control over combustion with predominantly higher HC and CO emissions.
GDI engine [70,73,74,104]	Accurate control over amount of fuel and injection timings, which affords better atomization and higher rates of fuel vaporization, so, improved fuel economy and improved transient response.	Difficulty in controlling the stratified charge combustion over the required operating range and relatively high light-load UBHC emissions along with high local NO*x* emission under stratified charge operation. Besides, soot formation for high-load operation and increased particulate emissions were noticeable.
Free piston engine [68,105]	Higher part load efficiency and multi-fuel possibilities due to combustion optimization flexibility and reduced frictional losses due to mechanical simplicity. In addition, reduced heat transfer losses and NO*x* emission due to faster power stoke expansion.	Loss of engine performance under transient conditions and greater cycle-to-cycle variations.
Lean burn engine [106,107]	Fuel flexibility, efficient combustion process and higher power with significant reductions in exhaust emissions.	Meeting the demands of practical lean combustion systems is complicated by low reaction rates, extinction, instabilities, mild heat release, and sensitivity to mixing.
VCR engine [98,108]	Control over engine performance and peak cylinder pressure, improved cold-start ability, multi-fuel capability, improved fuel economy and reduction of emissions.	Decrease in mechanical efficiency and suitable only for part load operation.

In lean-burn engines when the relative air–fuel ratio increases, the cycle-to-cycle variations exponentially increase. Therefore, optimizations of cycle-to-cycle variations are very much important to maximize the engine performance during lean-burn combustion. One way of controlling cyclic variations in lean-burn SI engines is by introducing gaseous fuels. Hence gaseous fuels are clean, economical and abundant fuels that can advance the lean operating limits and thus decrease the cyclic variations [88,89].

And, higher levels of NO*x* during the lean-burn combustion are mainly due to high combustion chamber temperature. Huang et al. [90–96] extensive studies on NO*x* emission control for lean-burn engines suggested solid oxide fuel cells and electrochemical-catalytic cells to effectively treat NO*x* emission. Also, NO*x* emission from lean-burn engines could be greatly reduced by applying two-stage combustion system [97].

3.6. Variable compression ratio (VCR) engine

In recent days, the effects of varying CR on engine performance have been extensively studied. This is due to the fact that operating at different CRs; the engine performance can be optimized for a full range of driving conditions [98]. In this perspective, the influences of VCR engine on engine operating characteristics are briefly discussed in the subsequent paragraphs.

Muralidharan and Vasudevan [99] investigated the impacts of varying CR on a VCR engine using waste cooking oil methyl esters and diesel blends. The analysis had been conducted at different CRs (18:1, 19:1, 20:1, 21:1 and 22:1). The experimental outcomes clearly exhibited a proportionate increase in BTE with an increase in CR. And, significant improvements in terms of fuel economy were also noticed. In addition, enhanced combustion characteristics were evident for VCR engine fueled with bio-diesel blends operated at higher CR.

In a similar way, the engine performance and emission characteristics of VCR engine fueled with waste cooking oil–bio-diesel blends were modeled using artificial neural network by Shivakumar et al. [100]. The test results showed that the relative mean error values of the proposed model in terms of performance and emissions were within the acceptable limits.

Moreover, the combustion instability and substantial increase in NO*x* emission at higher CR operation are in need of effective control techniques to optimize the engine characteristics in VCR engines [101].

On the whole, the operational behavior of different non-conventional engines dealt in this article has been keyed out in Table 2. Moreover, a detailed analysis on the inherent advantages and disadvantages of various non-conventional engines emphasized in this article are discussed in Table 3.

4. The future of IC engines

“Are engine development opportunities of the future down to the wire or up the ante?”

In this ‘viewpoint’, an in-depth analysis of the development opportunities, as well as future market trend of IC engines is discussed in detail in the succeeding paragraphs.

4.1. Emissions: the technology enforcer

Fortunately or unfortunately automobile emissions, drive present day engine technologies. As outlined by National Academy of Sciences, a concept of the standards-setting method for mobile-source emissions is “technology forcing”.

“The technology forcing refers the establishment by a regulatory agency of a requirement to achieve an emissions limit, within a specified time frame, that can be reached through use of unspecified technology or technologies that have not yet been developed for widespread commercial applications and have been shown to be feasible on an experimental or pilot-demonstration basis” [107].

Over the last 150 years, human activities are liable for the majority increase in Greenhouse gas emissions [109]. Among the other primary sources that contribute to Greenhouse gases, emissions from burning of fossil fuels need more effective control measures [110]. Year by year, rising global temperatures have been accompanied by dangerous shifts in climate and weather. A recent report by NOAA (*National Oceanic and Atmospheric Administration*) National Climatic Data Center on global climate analysis for the

Table 4
Total CO_2 emissions per country (2012).
Source: Olivier et al. [112].

Rank (largest emitters)	Country	CO_2 (megatons)
1	China	9860
2	US	5190
3	EU 27	3740
4	India	1970
5	Russian Federation	1770
6	Japan	1320
7	South Korea	640
8	Canada	560
9	Mexico	490
10	Indonesia	490
11	Brazil	460
12	Saudi Arabia	460
13	Australia	430
14	Iran	410
15	South Africa	330
16	Ukraine	320
17	Taiwan	280
18	Thailand	260

year 2013 disclosed that the year 2013 (tied with 2003) was recorded to be the fourth warmest year globally since records began in 1880 [111].

In concurrence, the global CO_2 emissions more than doubled over the last 40 years [112]. Also, in the year 2012, China, the United States and EU27 were the world's three largest CO_2 emitters (Table 4). However, it is anticipated that there would be a stable decline of emissions, if

- China achieves its own energy targets for 2015 and 2020.
- When the U.S. continues to increase its share of gas and renewables in the energy mix.
- EU by restoring the effectiveness of the Emissions Trading System [113].

In addition, according to the report on EU, the CO_2 reduction target was set at 50% by 2050 and around 20–30% by 2020 [114]. Besides, the U.S. Environmental Protection Agency (EPA) has recently finalized tight vehicle and fuel standards (release date: 03/03/2014) to substantially reduce emissions and protect public health [115].

4.2. Bio-fuels: a prudent step

In fact, bio-fuels would be one of the feasible solutions to cut Greenhouse gas discharges into the air. In this view, the researchers from the Swiss federal institute for materials science and technology have provided a perfect characterization of environmental benefits and costs of different bio-fuels. The survey disclosed that most bio-fuels considerably reduced the Greenhouse emissions when compared to fossil fuels. Also, the survey exposed that the fuels which showed over 50% reduction in Greenhouse gases when compared with fossil fuels were biodiesel prepared from several sources [116]. And, according to the estimate of The International Energy Agency (IEA), world bio-fuels consumption would annually increase at an average pace of 7%, which intends that by 2030 bio-fuels would account for approximately 5% of the total road transport [117]. Also, the projected world bio-fuels consumption up to 2015 and 2030 is presented in Table 5. One could comprehend from the table that there would be tripling of the world bio-fuels production from 16 Mtoe in 2004 to almost 55 Mtoe in 2015 and over 90 Mtoe in 2030. Contrariwise, it was recognized that each state faces several issues in implementing a viable bio-fuel market primarily due to climate, economic or supply security, food-fuel conflicts, and impacts of the bio-fuel policy on agricultural markets and land use [117–119].

Table 5
World Bio-fuels Consumption 2015 and 2030 in Mtoe (million tones of oil equivalent).
Source: Biofuels: policies, standards and technologies. World Energy Council 2010, obtained from IEA World Energy Outlook, 2006/updated 2009 [117].

	2004	2010	2015	2030
OECD*	**8.90**	**30.50**	**39.00**	**51.80**
North America	7.00	15.40	20.50	24.20
United States	*6.80*	*14.90*	*19.80*	*22.80*
Canada	*0.10*	*0.60*	*0.70*	*1.30*
Europe	2.00	14.80	18.00	26.60
Pacific	0.00	0.30	0.40	1.00
Transition economies	**0.00**	**0.10**	**0.10**	**0.30**
Russia	*0.00*	*0.10*	*0.10*	*0.30*
Developing countries	**6.50**	**10.90**	**15.30**	**40.40**
Developing Asia	0.00	1.90	3.70	16.10
China	*0.00*	*0.70*	*1.50*	*7.90*
India	*0.00*	*0.10*	*0.20*	*2.40*
Indonesia	*0.00*	*0.20*	*0.40*	*1.50*
Middle East	0.00	0.10	0.10	0.50
Africa	0.00	0.60	1.10	3.40
North Africa	0.00	0.00	0.10	0.60
Latin America	6.40	8.40	10.40	20.30
Brazil	*6.40*	*8.30*	*10.40*	*20.30*
World	**15.50**	**41.50**	**54.40**	**92.40**

* Organization for Economic Co-operation and Development.

Despite fragile bio-fuel market of present day, the demand for bio-fuels will grow all over the world in near future. For instance, the European Union aims at 10% bio-fuels of the entire road transport demand by 2020. The majority of bio-fuels will continue to be produced and consumed domestically, although the international trade in bio-fuels is also anticipated to extend appreciably. And, bio-ethanol produced from sugar cane will account for the major share of exports [117].

Also, the ethanol supply and demand outlook reveals that there will be regional inequity that will require trade between the regions. Specifically, North and Latin America are expected to have a surplus of ethanol production while Asia Pacific and the EU are expected to rely on imports. Both Africa and the Commonwealth of Independent States (CIS) should be balanced regions [120]. A recent study by Hart Energy [120] has forecasted a shortfall of 500 million gallons of ethanol for the EU by 2015 and 140 million gallons of ethanol for Japan in 2015. These two regions and countries are estimated to entail Brazilian ethanol for reasons of Greenhouse gas savings and sustainability. However, Brazilian ethanol exports are not expected to arrive at that level in 2015. Overall, the technology is a key component to enhance bio-energy production and increase the output without adverse economic and environmental implications.

Although the engine development opportunities of the future are not substantial due to the economic and environmental consequences, as well as the likely future opportunities in electric powertrains which would someday eventually replace IC engines. Nevertheless, the present day research and development activities can be centered on substantially reducing the emissions from automobile sources so as to safeguard the human race from the contrary effects of pollution.

5. Conclusions and recommendations

Engine developments, perhaps less fundamental, but however significant to the gradually extending internal combustion engine markets have continued ever since. Furthermore, during the last few decades, new factors for change have turned out to be imperative and now extensively affect engine design and operation. These factors are, first, the need to control the automotive contribution to air pollution and, second, the need to achieve momentous improvements in automotive fuel consumption. Based on the in-depth observations on engine technologies dealt in this article, the future investigations can be carried out on the following aspects to contest air pollution and to accomplish considerable improvements in automotive fuel consumption:

- The observed disadvantages concerning dual-fuel engines efficiency can be possibly mitigated by applying modifications on the engine tuning.
- In hydraulic free-piston engines, problems concerning cycle-to-cycle variations in piston dynamics and cycle stability have to be explored further.
- Extensive studies on GDI engine spray performance and PM emission control techniques have to be carried out.
- In HCCI engines, the most suitable methods to overcome the lack of combustion stability and greater suffering of HC and CO emissions during HCCI mode of combustion have to be investigated further.
- Development of sophisticated NO*x* emission control technologies is needed to combat high NO*x* levels during lean-burn combustion.
- In VCR engines, the optimum performance and emissions characteristics under various operating conditions with different bio-fuels have to be assessed.
- Also, the current bio-fuel technologies are not proposed up to the stipulated level. So, a proper planning measure, optimization techniques and standards are required to enforce such quality systems.
- And also, there is a need to develop highly consistent and competent technologies for advanced electric drive vehicles, as well as the problems related to power storage options in hybrid electric vehicles have to be extensively studied.

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